MARS SCIENCE LABORATORY PARACHUTE MODELING AND SIMULATION

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ABSTRACT

Due to unknown supersonic parachute area oscillations, a new set of bounding parachute loads are developed for use in the Mars Science Laboratory project. A series of analyses using a six degree-of-freedom simulation of the entry body are described and shown to be conservative in their assumptions. An area oscillation model is developed based on available historic flight test data from the Viking program. Loads derived from the entry body analyses are presented and the final margined design loads are shown to envelope all conditions expected during the parachutes phase of flight.

Key words: supersonic parachutes; area oscillations; lateral instability.

1. INTRODUCTION

The Mars Science Laboratory (MSL) is an ambitious mission that will land a 2,000 lbm, rover on the surface of Mars in the fall of 2012. MSL will use a $4.5m$ aeroshell and a 21.35 m reference diameter (D_o) disk-gap-band (DGB) parachute, both the largest ever flown. The parachute is mortar deployed on a velocity trigger at Mach 2.2 and is designed to survive a peak load of 65,000 lbf. The original structural design load case allowed for the possibility that the peak load could be channeled into a single bridle leg, but this was later deemed overly conservative, thus requiring this new loads analysis.

Viking-type DGB parachutes are known to undergo large-scale area oscillations at Mach numbers higher than 1.5 [2, 3]. These area oscillations are typically characterized by a rapid deflation, then re-inflation, and can result in a parachute load which is as large, or larger, than the initial opening load. Multiple load oscillations could occur during MSLs deceleration to Mach 1.5. These large changes in parachute loading can couple with the “wrist mode” of the MSL entry body where, as the two bodies descend, the entry body rotates about its center of mass. If the lander were to rotate to a large relative angle to the chute during a deflation event, the lander would experience a large, off-axis load on re-inflation, knowledge of which is critical to the design of the primary structure.

2. MODELING

In order to develop the set of bounding load cases, an area oscillation model was developed for incorporation into a 6 degree-of-freedom (DOF) Matlab simulation. While all three translational degrees of freedom have been modeled, unless otherwise stated, the only force that acts on the system is that of the parachute drag, which was modeled as acting entirely in the anti-velocity direction; this essentially restricts the system to one translational degree-of-freedom making the model effectively a 4 DOF simulation. The system geometry is shown in Figure 1.

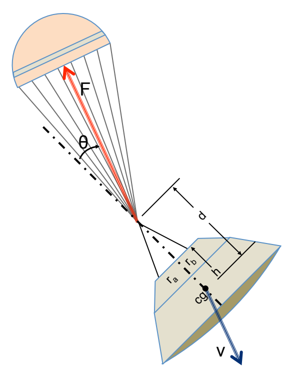

Figure 1. Two-body system Model.

Relative motion of the body to the chute is calculated using a nonlinear triple-bridle model where the bridle loads are calculated as if they were rigid members of a truss. However, as the bridles may only transmit tension, any members in compression are slack and carry no load. The truss solution is then recalculated with only the remaining tension members; up to two bridles may be slack at any time. Once the bridle loads and configuration have been determined, the torque applied to the entry body is calculated and used to drive the propagation of the entry body attitude.

2.1. Parachute Force and Area Oscillation Modeling

During the Viking supersonic parachute development, atmospheric test flights were conducted to characterize the supersonic behavior of DGB parachutes. The data from these tests was used to drive the development of the area profile generator, in particular, BLDT AV-1 and AV-4 which were both 16.1 m Viking DGB parachutes deployed at Mach 2.17 and 2.13 respectively [2, 3]. The parachute in the AV-1 test was damaged such that, while the data are still useful, the data from the AV-4 test are generally preferred. The data taken from the BLDT AV-4 report [3], and shown in Figure 2, provides the total parachute force, with obvious dropouts and overinflations.

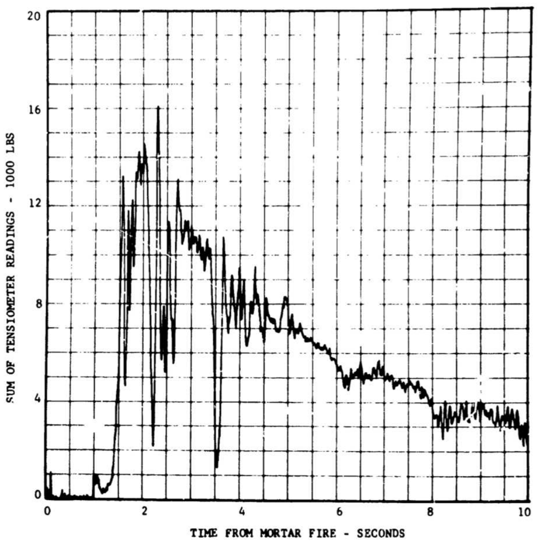

Figure 2. BLDT AV-4 Total Parachute Load

A randomized generator was used to drive the parachute force model due to the unpredictability of area oscillations, but rules are imposed on the generator such that it creates profiles that are in family with the BLDT AV-1/AV-4 parachute force data. Prior to the addition of area oscillations, the simulation uses a Pflanz inflation force profile [4] up to the point of peak inflation, which is always the design load of 65,000 lbf.

The onset of the area oscillations occurs only after the parachute has fully inflated, which is assumed to take place nominally. All area oscillations that follow have the characteristic of a deflation immediately followed by a re-inflation. This behavior was observed in both AV-1 and AV-4 and is commensurate with the idea that the parachute cannot inflate to a load level much beyond the nominal without first undergoing a collapse. The times and magnitudes of deflation and inflation are all random and independent, but this basic sequence is always the same and will hereafter be referred to as an "event". An outline of the event generation scheme is shown in Figure 3.

Flight tests have shown that significant area oscillation events occur only above approximately Mach 1.5. As such, a limit is imposed in the model that prevents events from occurring below the chosen Mach cutoff, which is a tunable model parameter, but never falls below Mach

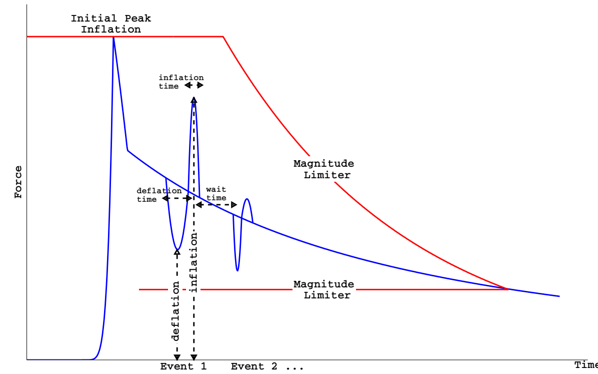

Figure 3. Profile generation controlling parameters

1.5. The same initial velocity, parachute area, drag coefficient, and density were used in the simulation so that the unmodulated deceleration of the vehicle is always the same. The number of events is a random variable, uniformly distributed between 1 and 10. However, the Mach cutoff is strictly enforced and a profile that is slated to have 10 events, for example, could well have fewer if all 10 do not fit into the allotted time spent above Mach 1.5.

A profile is created by stringing together either events or "wait" periods. A "wait" is simply a period of time, of randomly assigned duration based on a uniform distribution, in which an event is not taking place and the parachute force is simply given by qC_DA. One event is always prescribed to take place after initial peak inflation. Subsequent to this, sections are added to the profile, which are equally likely to be either wait periods or any additional events, until either the minimum Mach number has been reached or all events have taken place. After the Mach cutoff, the modulator is simply a wait period until the final time in the simulation.

The profile generator has three magnitude regimes, which dictate the allowable inflation/deflation over/under, the nominal force and the cutoff Mach for the events. The three regimes are low, mid, and high. The magnitude regimes specify functions of time that give the upper and lower bounds on the uniform distribution from which the magnitude of an event is chosen. As a result, all events in a high magnitude profile are not necessarily very large, but rather the range from which the event magnitudes are chosen is larger than either the low or the mid. The limits described for the deflation and inflation envelopes are illustrated in Figure 4 for the high, mid, and low ranges. Further information on the generation of parachute area oscillation profiles can be found in [1].

3. SIMULATION RESULTS

In order to address the sensitivity of the system to the magnitude regimes and the initial attitude at mortar fire, a Monte Carlo simulation consisting of 5000 cases was run at each area oscillation magnitude level. The initial atti-

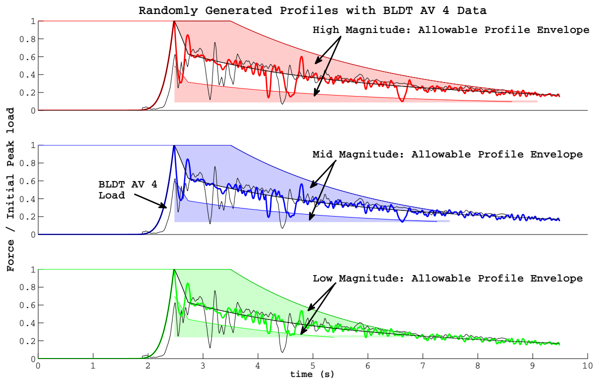

Figure 4. Randomly Generated Example Profiles

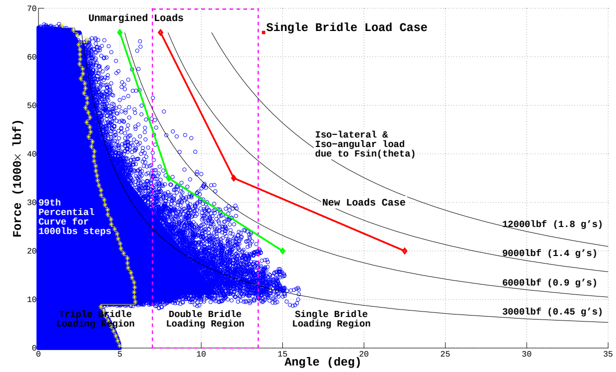

Figure 5. System Model.

tude of the entry body was uniformly distributed between $\pm 5^\circ$ relative to the velocity vector in order to match the mission requirement on attitude at the time of parachute mortar fire. However, at the time of the simulation, the MSL guidance team reported their estimated capability to be at $\pm 2.5^\circ$ at the three-sigma level making the $\pm 5^\circ$ spread a conservative set of initial conditions.

The data product that was ultimately most useful in creating new load cases is shown in Figure 5. This plot shows all 5000 complete time histories of the low event magnitude regime of the axial load (in thousands of lbf) vs. the total entry body angle of attack (in degrees). The line of yellow stars shows the 99th percentile angle for a force range of 1000 lbf. This line has been used in bounding the loads in order avoid setting the design point too high due to outlier cases. The original load case of 65,000 lbf on a single bridle, corresponding to 13.83° entry body angle, is shown in Figure 5 as a red square for reference.

Based on the BLDT AV-4 profile, the low event envelope was chosen as the most likely to occur, with the mid envelope providing margin on event modeling. Therefore, in order to create new load cases, a bi-linear bound was placed on the low magnitude curve, represented by the green lines in Figure 5. In addition, 50% was added to the angle specification in order to carry margin in the loads cases due to the relative uncertainty in the load prediction. These three points (the bounding curve shown in red) represent the new parachute load case, which is summarized in Table 1.

Table 1. MSL New Design Loads.

Unmargined Loads	Margined: New Load case
65,000 lbf at 5°	65,000 lbf at 7.5°
35,000 lbf at 8°	35,000 lbf at 12°
20,000 lbf at 15°	20,000 lbf at 22.5°

4. ADDITIONAL MODELING

The range of output behaviors exhibited by the model are, naturally, highly dependent on the force profiles which are used as inputs. There is uncertainty in the values used to create the force profiles due to the very limited data available. However, the identified controlling characteristics of area oscillations accurately reproduce features of the BLDT data and the area oscillation generator has the capability of varying these characteristics in order to create a wide variety of believable force profiles. By allowing those characteristics to vary over a range larger than that observed in available data and by allowing a large initial attitude, the new load cases constitute a set of reasonable and conservative design points. The additional 50% margin on the new load case guards against future discovery and unmodeled behaviors of the system. A few of these behaviors were added to the system model after the new load case was established. One of these additions is presented below as further justification of the conservatism of the bounding load case.

4.1. Lateral Parachute Motion

A simple model of lateral parachute motion was added to the simulation to determine how detrimental lateral instability could be to the entry body loading. The parachute force was allowed to act in a direction slightly off that of the anti-velocity vector, thus allowing motion in all three translational directions. No changes were made to the actual equations of motion, but all six degrees of freedom were made active. Examination of the BLDT data showed the total parachute pull angle (the angle between the chute and the body) to be approximately 3 degrees with oscillations of ± 1 degree at approximately 3 Hz [3]. This motion was modeled as the parachute moving in a circle (coning) at that particular angle of attack with very low frequency. Based on the considerably larger apparent mass of the MSL parachute compared to the BLDT chutes, lower frequencies of oscillation were deemed to be more likely. Three magnitude regimes were created, and three frequencies of oscillation which can be independently varied in order to judge sensitivity. The results for the mid magnitude regime are presented, which used a trim and oscillation angle of $3 \pm 1\,^{\circ}$, and oscillation and coning frequencies of 3 Hz and 0.01 Hz, respectively.

There is very little data to inform the choice of oscillation magnitude/frequency and no analytical model to predict lateral parachute motion due to the lack of measured dynamic stability derivatives and the inherent chaotic motion of supersonic parachutes. For these reasons, this effort was in no way meant to be an exhaustive study of lateral parachute motion. However, the BLDT data was used with some margin on either side in order to address the lien on lateral motion and show that the chosen load cases are not completely overrun when the system is further stressed. A trace of the parachute center of mass position from a randomly generated profile is shown in Figure 6.

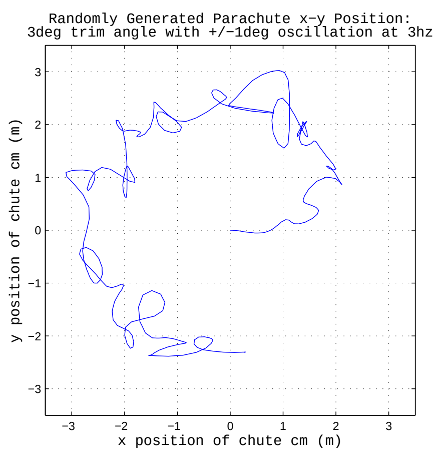

Figure 6. Parachute position due to lateral instability

Another simulation set was created with the addition of lateral parachute motion at two frequencies. A comparison is made between the mid axial event magnitude case with no lateral motion in Figure 7, and the mid axial event magnitude case with lateral motion at the mid lateral magnitude range at 3 Hz in Figure 8. With the added lateral parachute motion, the angles of the outliers are increased and the 99th percentile line does start to encroach on the unmargined design load. Increasing the magnitude and frequency of the lateral motion to a higher level can cause the 99th percentile to violate the unmargined bounds (simulated but not shown), but without further data to aid in modeling the lateral motion, these two magnitude/frequency profiles represent the best available rough estimate and the chosen design loads should be robust to lateral motion of this magnitude.

5. CONCLUSIONS

The new design loads were shown through simulation to bound the expected dynamics due to supersonic area oscillations. As this load case provides adequate margin suitable for design of the MSL vehicle interfaces and primary structure, these loads have been adopted by the MSL project for vehicle design. This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

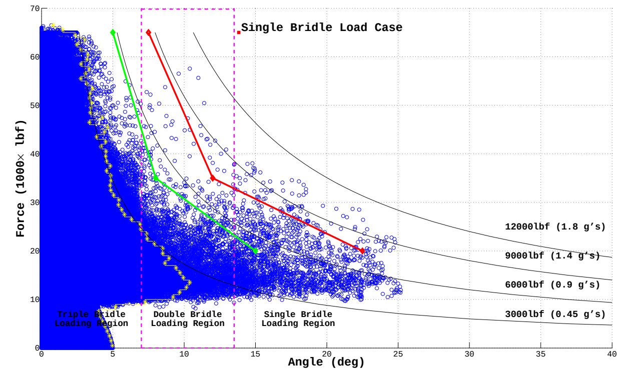

Figure 7. Mid magnitude axial events only

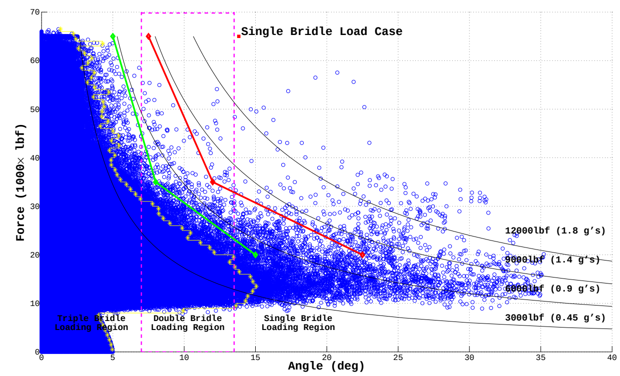

Figure 8. Mid magnitude axial events, with 3 Hz, mid magnitude lateral parachute motion

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